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Li et al.

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(54) **BACK EMF MONITOR FOR MOTOR CONTROL**

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H02P 7/29 (2006.01)

(52) **U.S. Cl.**
CPC ***H02P 7/29*** (2013.01)

(58) **Field of Classification Search**
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USPC 318/400.34
See application file for complete search history.

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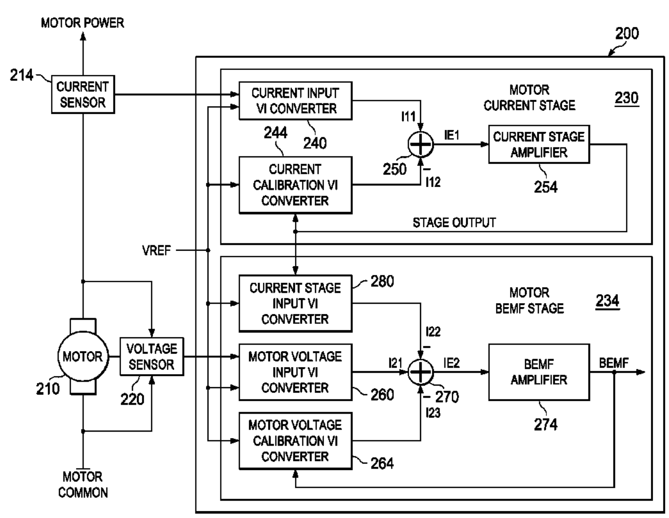
(57) **ABSTRACT**

An integrated circuit includes a motor current input voltage-to-current (VI) converter that receives a motor current sensor voltage from a motor and a reference voltage to generate an output current related to a motor's current. A motor current calibration VI converter compensates for errors in the motor current input VI converter and generates a calibration output current based on the reference voltage, wherein the output current and the calibration output current are combined to form an estimate of the motor's current.

1 Claim, 7 Drawing Sheets



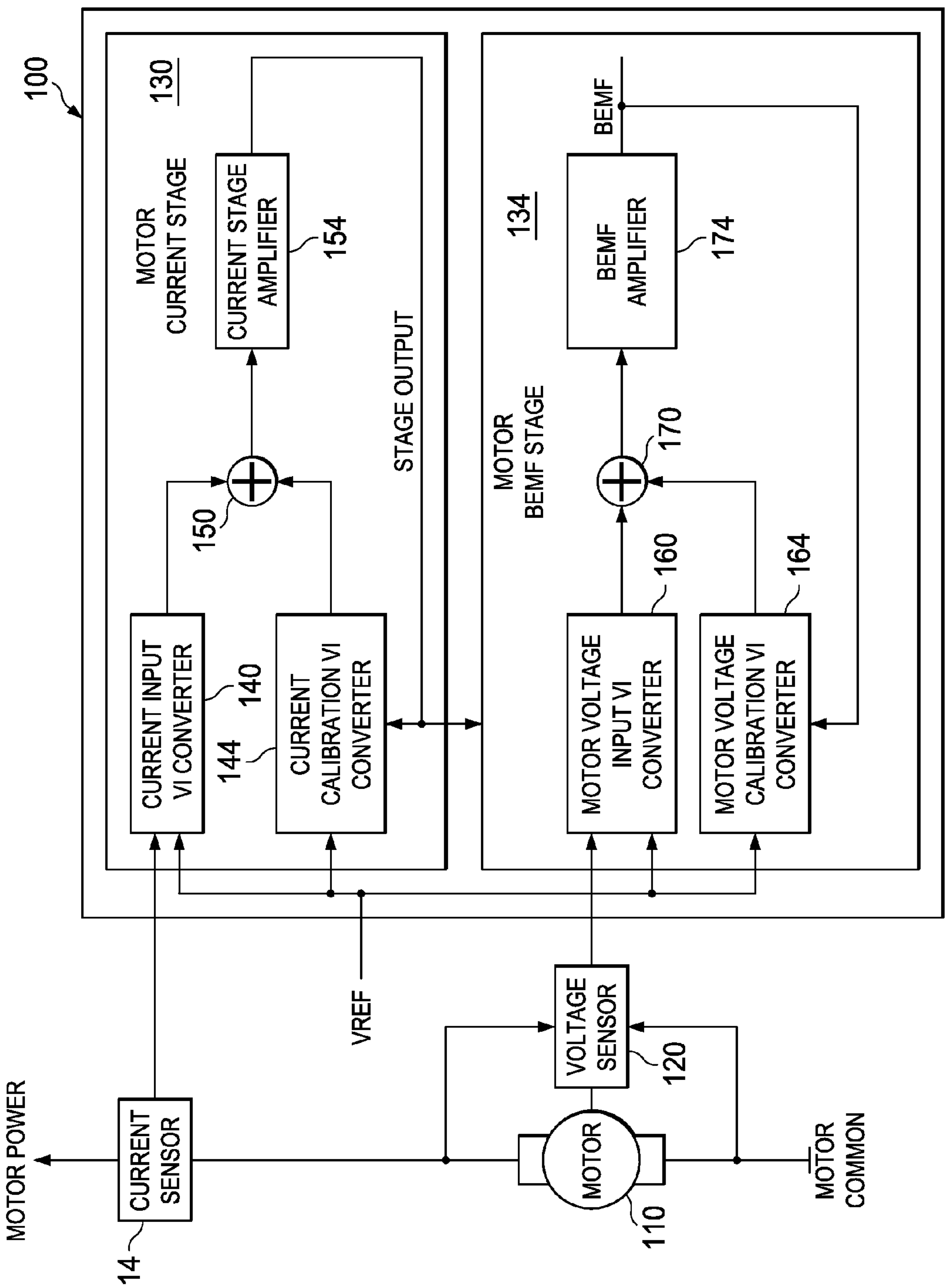
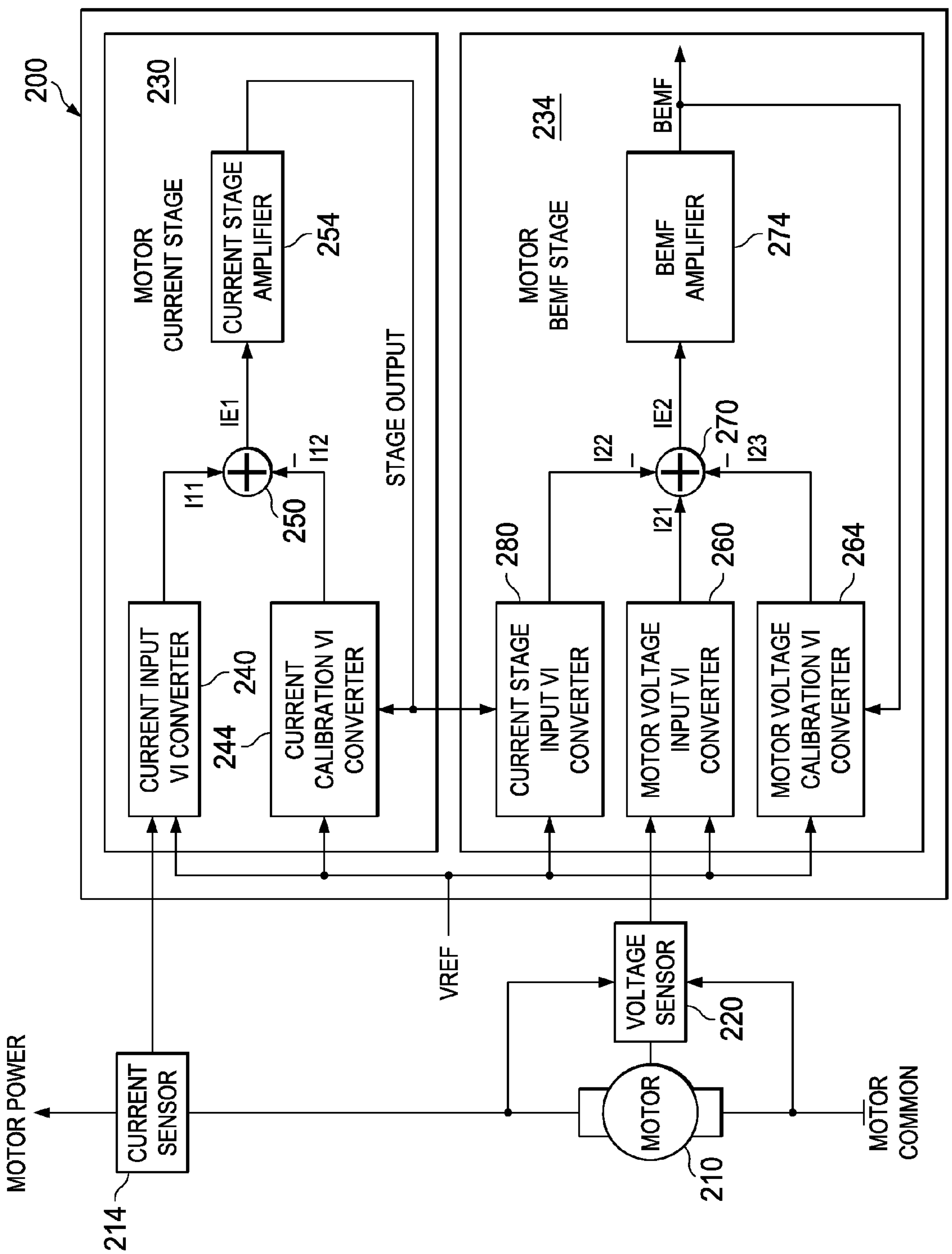

100
MOTOR CURRENT STAGE
130
CURRENT STAGE AMPLIFIER
154
STAGE OUTPUT
150
CURRENT INPUT VI CONVERTER
140
144
CURRENT CALIBRATION VI CONVERTER
MOTOR BEMF STAGE
134
BEMF
BEMF AMPLIFIER
174
170
160
164
MOTOR VOLTAGE INPUT VI CONVERTER
MOTOR VOLTAGE CALIBRATION VI CONVERTER
VREF
VOLTAGE SENSOR
120
MOTOR POWER
CURRENT SENSOR
114
MOTOR
110
MOTOR COMMON

FIG. 1

FIG. 2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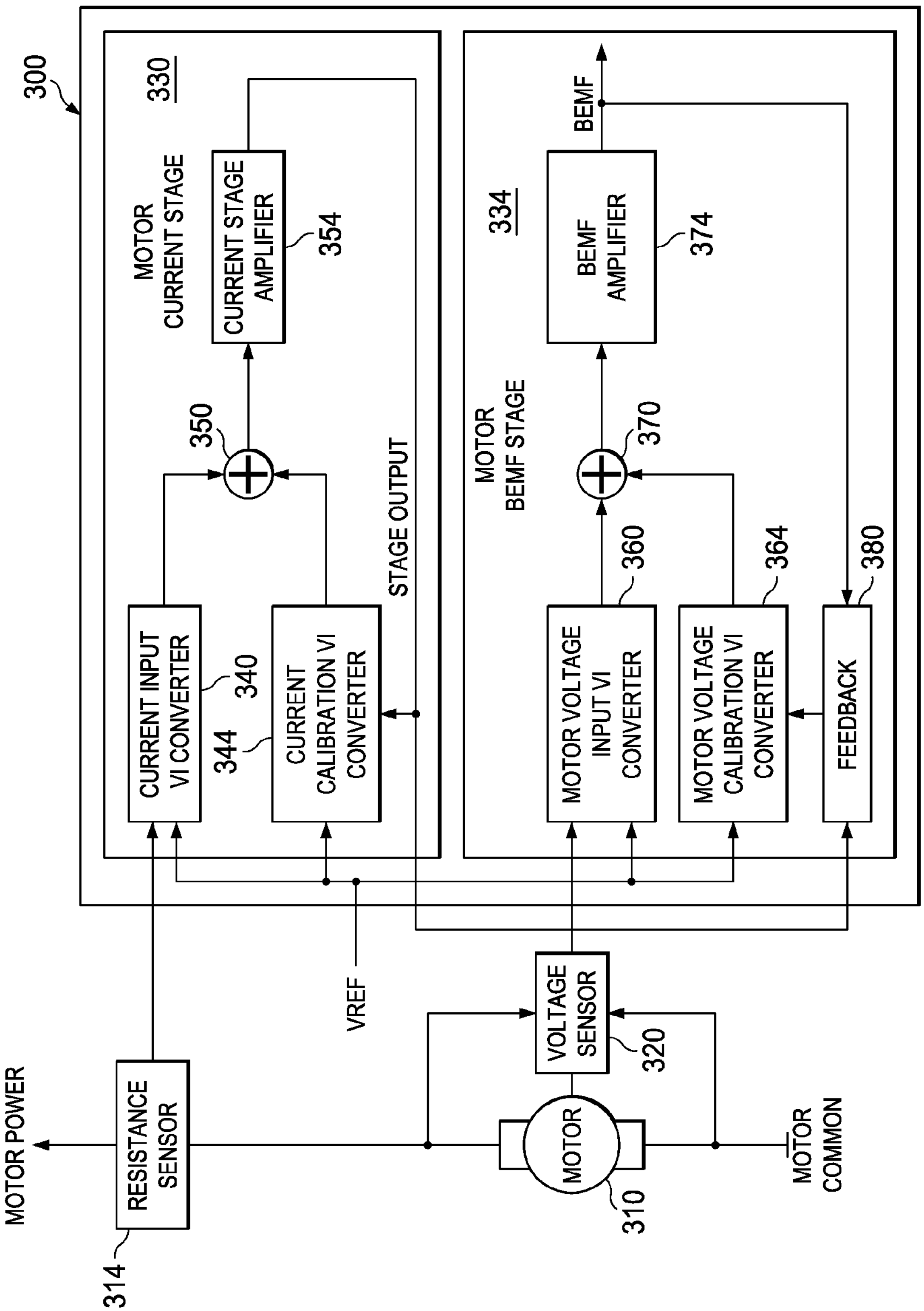
230
MOTOR CURRENT STAGE
CURRENT STAGE AMPLIFIER
254
IE1
I11
I12
250
STAGE OUTPUT
CURRENT INPUT VI CONVERTER
240
244
CURRENT CALIBRATION VI CONVERTER
234
MOTOR BEMF STAGE
BEMF
BEMF AMPLIFIER
274
IE2
270
I22
I21
I23
280
260
264
CURRENT STAGE INPUT VI CONVERTER
MOTOR VOLTAGE INPUT VI CONVERTER
MOTOR VOLTAGE CALIBRATION VI CONVERTER
VREF
VOLTAGE SENSOR
220
MOTOR POWER
CURRENT SENSOR
214
MOTOR
210
MOTOR COMMON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330
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340
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344
350
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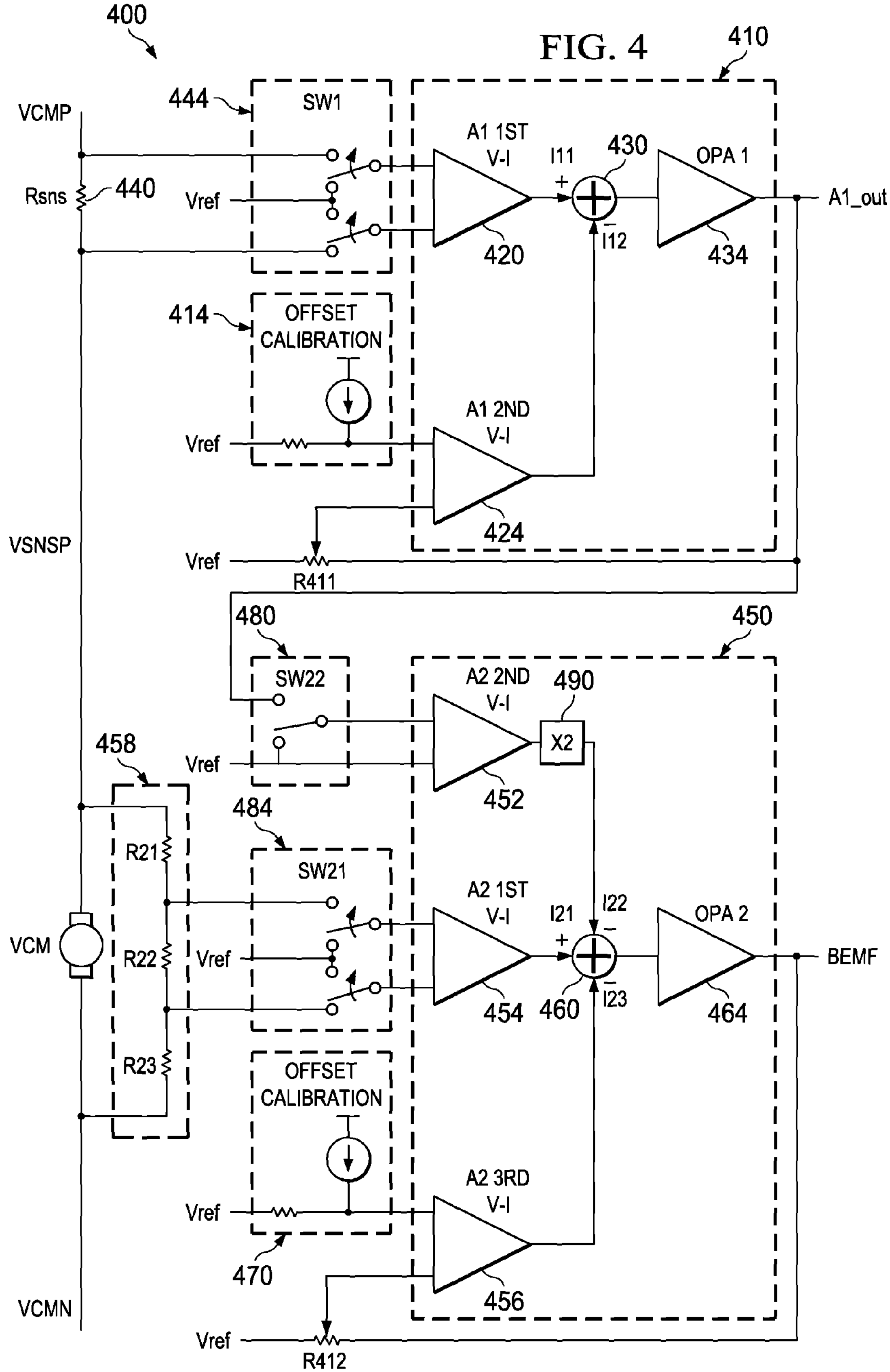
354
STAGE OUTPUT
MOTOR BEMF STAGE
334
MOTOR VOLTAGE INPUT VI CONVERTER
360
MOTOR VOLTAGE CALIBRATION VI CONVERTER
364
FEEDBACK
380
370
BEMF AMPLIFIER
374
BEMF
VREF
MOTOR POWER
RESISTANCE SENSOR
314
MOTOR
310
VOLTAGE SENSOR
320
MOTOR COMMON

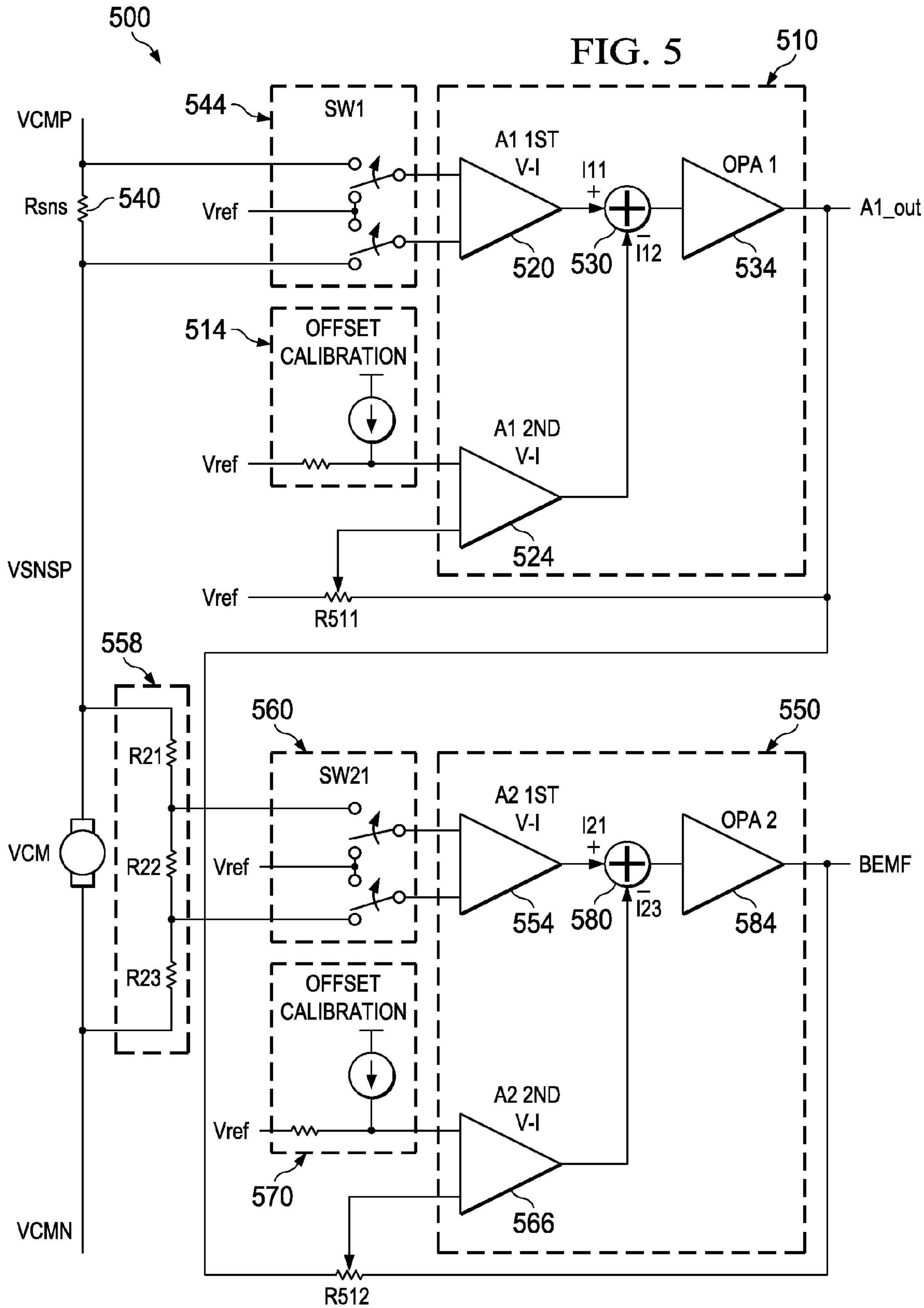
FIG. 3

FIG. 4



400
410
444
SW1
VCMP
Rsns
440
Vref
A1 1ST V-I
I11
430
OPA 1
A1_out
I12
420
434
414
OFFSET CALIBRATION
A1 2ND V-I
424
VSNSP
R411
480
450
SW22
A2 2ND V-I
490
X2
452
458
484
R21
SW21
A2 1ST V-I
I21
I22
OPA 2
VCM
R22
BEMF
I23
454
460
464
R23
A2 3RD V-I
470
456
VCMN
R412

FIG. 5



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SW1
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A1 1ST
V-I
I11
OPA 1
A1_out
520
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I12
534
514
OFFSET
CALIBRATION
Vref
A1 2ND
V-I
524
VSNSP
Vref
R511
558
560
550
R21
SW21
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V-I
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VCM
R22
Vref
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V-I
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VCMN
R512

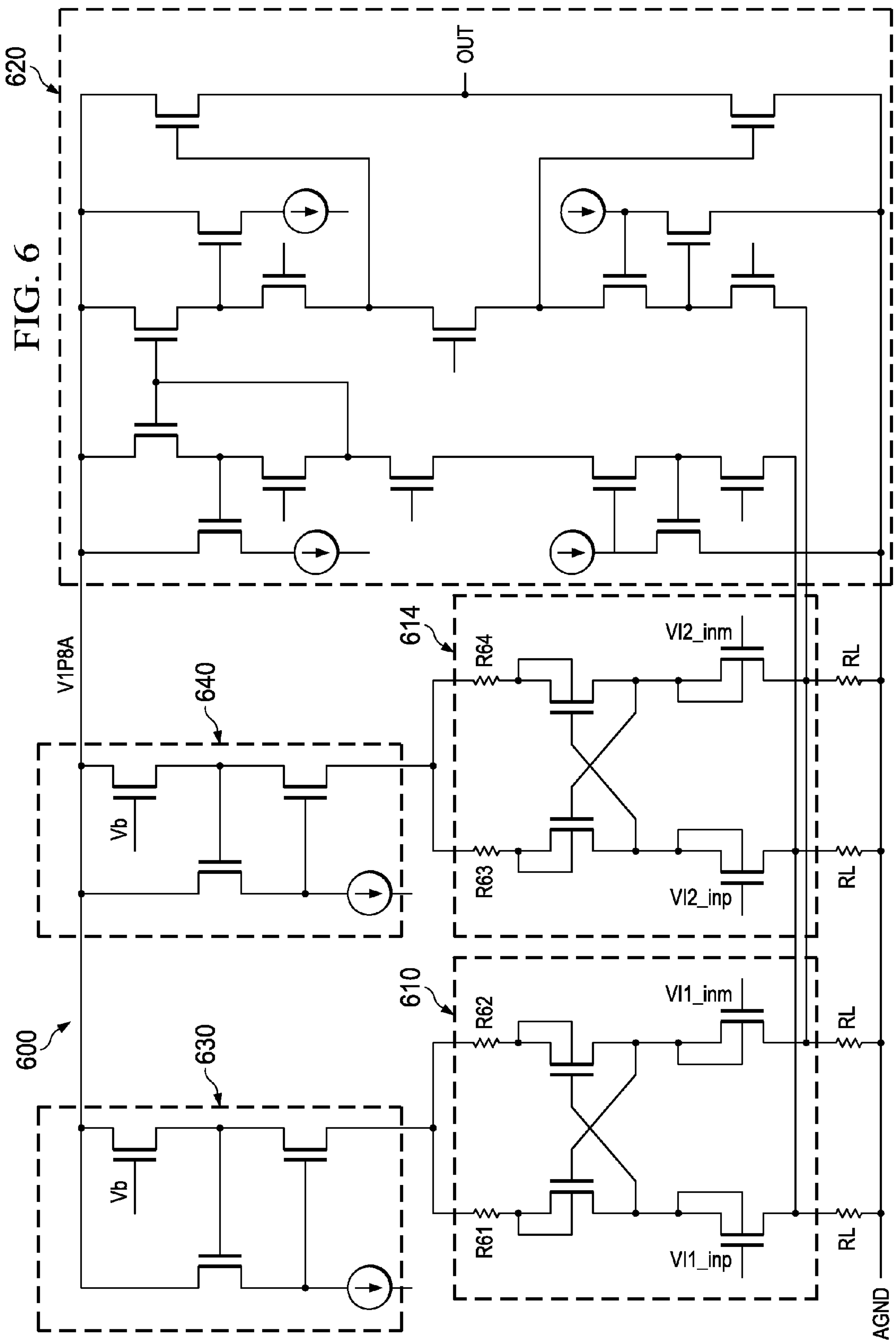
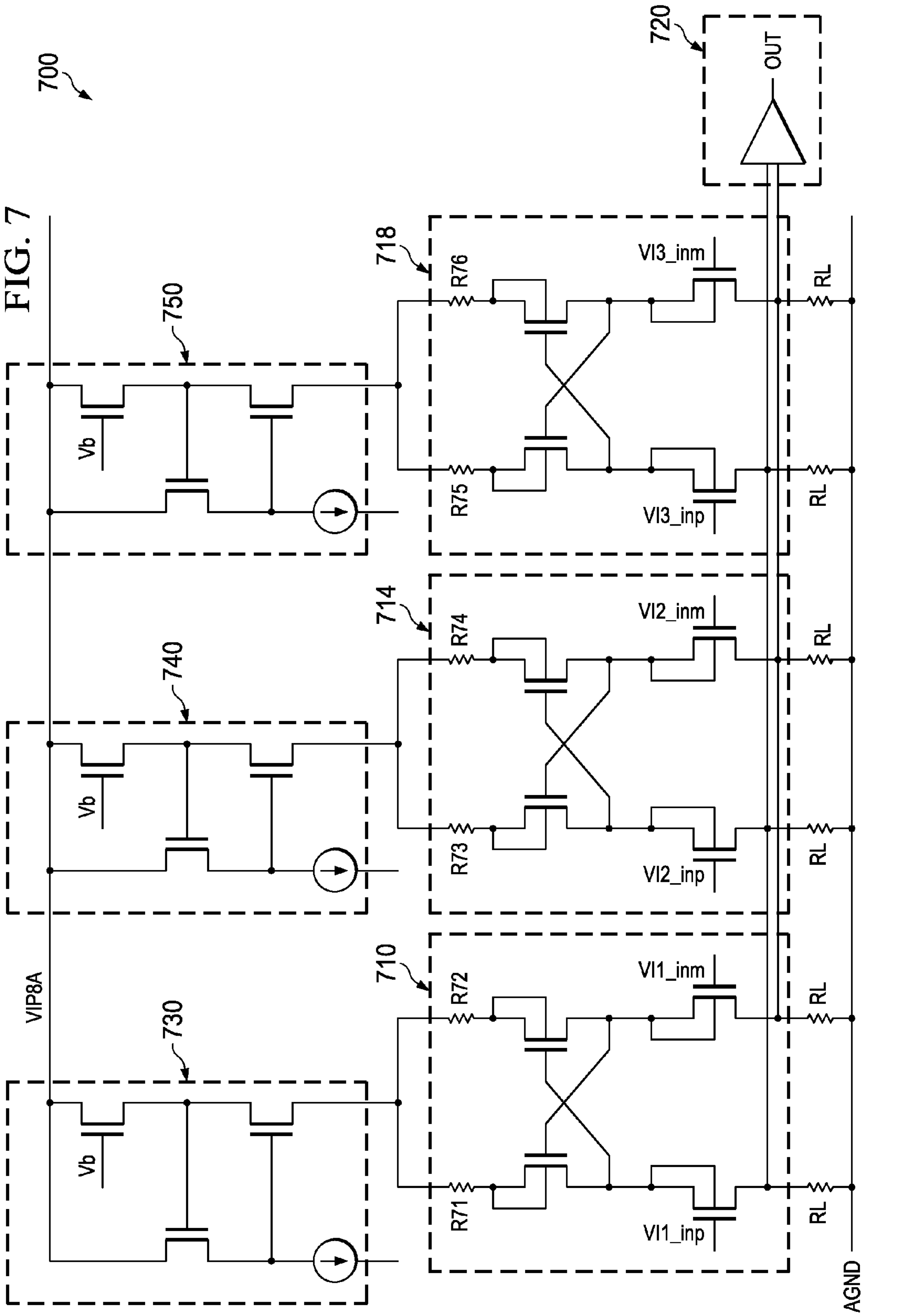

620
OUT
V1P8A
640
614
R64
VI2_inm
R63
VI2_inp
Vb
RL
RL
600
630
610
R62
VI1_inm
R61
VI1_inp
Vb
RL
RL
AGND

FIG. 6


700
720
OUT
718
R76
R75
VI3_inm
VI3_inp
RL
RL
750
Vb
714
R74
R73
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VI2_inp
RL
RL
740
Vb
710
R72
R71
VI1_inm
VI1_inp
RL
RL
730
Vb
VIP8A
AGND

FIG. 7

BACK EMF MONITOR FOR MOTOR CONTROL

RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application No. 61/718,364, filed Oct. 25, 2012 and entitled BEMF MONITOR ARCHITECTURE USING V-I CONVERTERS, which is incorporated herein by reference in its entirety.

TECHNICAL FIELD

This disclosure relates to drive control circuits, and more particularly to integrated circuits to monitor back electromotive force (BEMF) of a motor.

BACKGROUND

In order to control a motor, such as hard disk drive motor, a voltage known as back electromotive force (BEMF) can be computed for the respective motor. Such computation is performed by a monitor circuit in the analog domain where a first analog stage estimates the motor's resistance and a second analog stage estimates the motor's voltage. The motor voltage and resistance computation can then be combined in the second analog stage to form the BEMF voltage computation which is provided to a motor controller to facilitate control of the motor. Presently, each analog stage employs multiple front end resistors to perform voltage-to-current conversions from motor sensing elements in order to determine the motor resistance and voltage. The front end resistors require precise matching to enable accurate measurements and this can lead to various issues.

SUMMARY

This disclosure relates to back electromotive force (BEMF) monitor circuits. In one example, an integrated circuit includes a motor current input voltage-to-current (VI) converter that receives a motor current sensor voltage from a motor and a reference voltage to generate an output current related to a motor's current. A motor current calibration VI converter compensates for errors in the motor current input VI converter and generates a calibration output current based on the reference voltage, wherein the output current and the calibration output current are combined to form an estimate of the motor's current.

In another example, an integrated circuit includes a motor voltage input voltage-to-current (VI) converter that receives a motor voltage sensor voltage from a motor and a reference voltage to generate an output current related to the motor's voltage. A motor voltage calibration VI converter compensates for errors in the motor voltage input VI converter and generates a calibration output current based on the reference voltage, wherein the output current and the calibration output current are combined to form an estimate of the motor's voltage.

In yet another example, an integrated circuit includes a motor current input voltage-to-current (VI) converter that receives a motor current sensor voltage from a motor and a reference voltage to generate an output current related to a motor's current. A motor current calibration VI converter compensates for errors in the motor current input VI converter and generates a calibration output current based on the reference voltage, wherein the output current and the calibration output current are combined to form an estimate of the

motor's current. A motor voltage input voltage-to current (VI) converter receives a motor voltage sensor voltage from the motor and a reference voltage to generate an output current related to the motor's voltage. A motor voltage calibration VI converter compensates for errors in the motor voltage input VI converter and generates a calibration output current based on the reference voltage. The estimate of the motor's current and the estimate of the motor's voltage are combined to form an estimate of the motor's back electromotive force (BEMF) voltage.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates an example of an integrated circuit back electromotive force (BEMF) monitor.

FIG. **2** illustrates an example of an integrated circuit that includes back electromotive force (BEMF) monitor further implementing an additional VI converter in a motor BEMF stage to compute motor BEMF.

FIG. **3** illustrates an example of an integrated circuit that includes back electromotive force (BEMF) monitor further implementing feedback to a motor calibration converter in a motor BEMF stage to compute motor BEMF.

FIG. **4** illustrates a circuit example of a back electromotive force (BEMF) monitor that employs an additional VI converter in a motor BEMF stage to compute motor BEMF.

FIG. **5** illustrates a circuit example of a back electromotive force (BEMF) monitor that employs feedback to a motor calibration converter in a motor BEMF stage to compute motor BEMF.

FIG. **6** illustrates still another example of a four input operational amplifier that can be employed in a BEMF monitor circuit.

FIG. **7** illustrates an example of a six input operational amplifier that can be employed in a BEMF monitor circuit.

DETAILED DESCRIPTION

A monitor circuit is provided for determining back electromotive force (BEMF) voltages for motor control, such as a hard disk drive controller. The monitor circuit can be provided as an integrated circuit that employs voltage-to-current (VI) converters at its front end to a motor current and voltage to enable an analog computation of the motor's BEMF voltage. The VI converters in the monitor circuit perform voltage-to-current conversions from sensors via high impedance inputs that obviate the need to have matched resistor networks to perform the conversions. The VI converters can be accurately calibrated while utilizing a smaller amount of integrated circuit area than matched resistor network circuits. The VI converters can also be configured to provide improved common mode rejection over resistive network implementations.

In resistance front-end BEMF monitor circuits, for example, to achieve the required common mode rejection ratio (CMRR) specification, analog stage front end resistors have to be accurately matched. In an integrated circuit, the resistor matching level

$$\sigma \propto \frac{1}{\sqrt{WL}},$$

where W and L are the width and length of the resistors. This implies that enhancing matching level (i.e., CMRR) by a factor of two requires four times larger area consumption. To further improve the resistor matching level, a resistor trimming circuit may be employed. Both resistor matching and trim circuit requirements are very area-demanding for an integrated circuit, which is undesirable in a high-volume product line, for example a HDD (Hard Disk Drive) Servo IC product. Resistor matching accuracy and trimming accuracy are also constrained by circuit temperature coefficient and voltage coefficient effects. Thus, resistor matching requirements place considerable strains on suitable integrated circuit implementations for a high-performance BEMF monitor. The circuits described herein obviate the requirement for the front-end accurately-matched resistors as well can also provide enhanced BEMF computations.

FIG. **1** illustrates an example of an integrated circuit **100** for a back electromotive force (BEMF) monitor. A motor **110** is energized via motor power and common connections which can be supplied from a controller (not shown). When the motor **110** is in motion, it generates BEMF voltage on the coil inside the motor and the BEMF voltage is usually proportional to the motor speed. The target is to compute the BEMF voltage through the voltage measured cross the motor **110** and the current flowing through the motor. Current from the motor **110** is sensed via a current sensor **114** and voltage from the motor is sensed via voltage sensor **120**. The current sensor **114** and/or voltage sensor **120** can be implemented by resistive networks, for example. The current sensor **114** generates a voltage proportional to the motor current where a motor current stage **130** determines a value for the motor's current. Output from the motor current stage **130** is fed to a motor BEMF stage **134** that determines motor voltage via the voltage sensor **120**. Additionally, the motor BEMF stage **134** combines the current estimate from the motor current stage **130** with the motor voltage determination to compute a motor BEMF voltage shown as BEMF that can be subsequently sent to a controller to control the motor **110**.

A motor current input voltage-to-current (VI) converter **140** in the motor current stage **130** receives a voltage from the current sensor **114** and a reference voltage VREF to generate an output current related to the current through the motor. The reference voltage VREF can be a periodically switched value that is employed across the circuit **100** to enable determination of BEMF, such as can vary depending on an operating mode of the circuit **100**. A current calibration VI converter **144** can be configured to compensate for errors (e.g., gain errors, CMRR) in the motor current input VI converter **140** and generate a calibration output current based on the reference voltage VREF and the feedback from the output of current stage amplifier **154**. The output current and the calibration output current of converters **140** and **144** are combined at a summing node **150** such as corresponding to a difference between the input current and the calibration current. The summing node **150** can in turn provide a corrected indication of motor current. As disclosed herein, the motor current and corresponding motor voltage can be utilized to provide an estimate of the motor's resistance, which is employed to determine the BEMF of the motor **110**. Output from the summing node **150** is fed to a current stage amplifier **154** which generates an output that is fed back to the motor current calibration VI converter **144** and is also provided to the motor BEMF stage **134** for determination of motor BEMF.

A motor voltage input VI converter **160** in the motor BEMF stage **134** receives a motor sensor voltage from the voltage sensor **120** and the reference voltage VREF to generate an output current related to the motor's voltage. A motor voltage calibration VI converter **164** compensates for errors (e.g., gain errors, CMRR) in the motor voltage input VI converter **160** and generates a calibration output current based on the reference voltage VREF and the feedback from the output of BEMF amplifier **174**. The output current and the calibration output current from VI converters **160** and **164** are combined at summing node **170** (e.g., based on a difference between the respective signals) to form an estimate of the motor's BEMF voltage. Output from the summing node **170** is fed to BEMF amplifier **174** which generates a BEMF voltage output that can be employed by a controller to control the motor **110**.

In order to determine BEMF, output from the motor current stage **130** can be combined with the voltage determinations in the motor BEMF stage **134**. The output from the current stage amplifier **154** can be processed according to alternative configurations in the motor BEMF stage **134** to determine the BEMF (See FIGS. **2** and **3** below). In one example configuration, the current stage output is processed in the motor BEMF stage **134** via an additional VI converter whose output is summed along with currents representing motor voltage and calibration at **170** (See FIGS. **2** and **4**). In another example configuration, the current stage output is utilized by the motor voltage calibration VI converter **164** as feedback which can be combined with the BEMF feedback from the BEMF amplifier **174** (See FIGS. **3** and **5**).

As a further example, VI converters **140** and **144** can be differential amplifiers. For instance, a differential amplifier for the motor current VI converter **140** can have one input of the differential amplifier receive voltages from the current sensor **114** and another input to receive the reference voltage VREF. Similarly, the motor current calibration VI converter **144** can have one input of the differential amplifier receive the reference voltage VREF and another input to receive sense stage output as feedback from the current stage amplifier **154**. Outputs from both differential amplifiers can be coupled to form the summing node **150** as will be illustrated and described with respect to FIGS. **6** and **7** below. The motor current stage **130** can thus be configured as a four input operational amplifier having two pairs of differential inputs and a single output. Similarly, the motor BEMF stage **134** can be configured as a four input amplifier or a six input amplifier depending on the configuration of the stage as will be illustrated and described below.

By utilizing the VI converters **140**, **144**, **160**, and **164** in lieu of conventional front end resistive networks, performance of the circuit **100** can be improved in terms of smaller integrated circuit area and improved common mode rejection characteristics. In one example, the motor **110** can be a Voice Coil Motor (VCM) where the circuit **100** can be employed as part of a hard disk drive (HDD) servo integrated circuit, for example. The BEMF monitor operation can include two steps, that is, gain calibration mode (to calibrate the gain of motor current stage **130**) and BEMF monitor mode (to compute motor BEMF voltage). In the first step, in the gain calibration mode, a given amount of current I_1 is forced into the motor path while the motor **110** is kept still so that its BEMF voltage is zero. The motor voltage sensed at sensor **120** is $I_1*R_M+L_M\cdot(dI_1/dt)$, where R_M and L_M are respectively resistance and inductance of the motor **110**. Since the voltage is usually sensed after motor current settles down, i.e., $dI_1/dt=0$ so item $L_M\cdot(dI_1/dt)$ is negligible in the context. Meanwhile, the motor current sensed at current sensor **114** I_1*R_{SNS}, where R_{SNS} is the sense resistance, is amplified by the gain G of stage **130**. The stage **130** output $I_1*R_{SNS}*G$ is fed to motor BEMF stage **134** to be subtracted from the motor voltage I_1*R_M. In other words, motor BEMF stage **134** performs a calculation $I_1*R_M-I_1*R_{SNS}*G$. The goal is to digitally adjust the gain G of current stage **130** so that stage **134** output

I_1*R_M–I_1*R_{SNS}*G is about equal to zero. Thus, gain of current stage **130** G=R_M/R_{SNS} is digitally calibrated and memorized.

In step **2**, in the BEMF monitor mode, an arbitrary current i is dumped into motor path by controller (not shown) and motor is driven to a certain speed and it generates corresponding BEMF voltage. The motor voltage sensed at voltage sensor **120** is V_{BEMF}+L_M*(di/dt)+i*R_M, while the motor current sensed at **114** is gained up G times in the motor current stage **130**. The on-time computation performed in BEMF stage **134** is (motor voltage sensed in sensor **120**)–(motor current sensed in sensor **114**)*G=(V_{BEMF}+L_M*(di/dt)+i*R_M)–(i*R_{SNS})*G=V_{BEMF}, where G=R_M/R_{SNS} is digitally calibrated and memorized in the first step. That is, the output of stage **134** is an estimation of BEMF voltage of motor **110**, assuming the sense and computation operations are performed after i settles down and (di/dt)=0.

In one example, the circuit **100** can be provided as a circuit (e.g., integrated circuit, discrete circuit, combination of integrated circuit and discrete circuits) for monitoring motor BEMF. This can include different analog and/or digital circuit implementations. For instance, in some cases, field effect transistors (e.g., N-type or P-type) can be employed and in other cases junction transistors or diodes employed.

FIG. **2** illustrates an example of an integrated circuit **200** for a back electromotive force (BEMF) monitor that employs an additional VI converter in a motor BEMF stage to compute motor BEMF. A motor **210** is energized via motor power and common connections which can be supplied from a controller (not shown). Current from the motor **210** is sensed via current sensor **214** and voltage from the motor is sensed via voltage sensor **220**, where a motor current stage **230** determines the motor's current. Output from the motor current stage **230** is fed to a motor BEMF stage **234** that determines motor voltage via the voltage sensor **220**. Additionally, the motor BEMF stage **234** combines the current estimate from the motor current stage **230** with the motor voltage determination to compute a motor BEMF voltage shown as BEMF that can be sent to a controller to control the motor **210**.

A first voltage-to-current converter, current input VI converter **240**, in the sense stage **230** receives a motor current sensor voltage from the current sensor **214** and a reference voltage VREF to generate an output current I_{11} related to the motor's current. A second VI converter, motor current calibration VI converter **244**, compensates for errors (e.g., gain errors, CMRR) in the motor current input VI converter **240** and generates a calibration output current I_{12} based on the reference voltage VREF and the feedback from output of current stage amplifier **254**. The output current I_{11} and the calibration output current I_{12} of converters **240** and **244** are combined at a summing node **250**. Output from the summing node **250** is fed to a current stage amplifier **254** which generates an output that is fed back to the motor current calibration VI converter **244** and is also provided to the motor BEMF stage **234** for analog computation of motor BEMF. The currents at summing node **250** are connected in such a manner that calculation I_{E1}=I_{11}–I_{12} is performed. The error current I_{E1} is amplified by current stage amplifier **254** and fed back (negative feed-back loop with high gain) to the input of the calibration VI converter **254**, and then I_{12} is controlled to force I_{E1}=0, that is, force I_{12}=I_{11}. Since these two VI converters' input/output transfer functions are similar, above current computation is equivalent to making voltage input of VI **244** a copy of voltage input of VI **240**.

A first VI converter, motor voltage input VI converter **260** in the motor BEMF stage **234**, receives a motor sensor voltage from the voltage sensor **220** and the reference voltage VREF to generate an output current I_{21} related to the motor's voltage. A second VI converter, current stage input VI converter **280**, receives the output of current stage **230** and the reference voltage VREF to generate an output current I_{22} related to the motor's current. A third VI converter, motor voltage calibration VI converter **264**, receives the output of BEMF amplifier **274** and the reference VREF to generate a calibration output current I_{23}. The output current I_{21} and I_{22} of VI converter **260** and **280**, and the calibration output current I_{23} from VI converter **264** are combined at summing node **270** to form an estimate of the motor's BEMF voltage. The currents at summing node **270** are connected in such a manner that calculation $I_{E\ 2}$=I_{21}–I_{22}–I_{23} is performed. The error current I_{E2} is amplified by BEMF amplifier **274** and fed back (negative feed-back loop with high gain) to the input of the calibration VI converter **264**, and then I_{23} is controlled to force I_{E2}=0, that is, force I_{23}=I_{21}–I_{22}. Since the three VI converters' transfer function are nominally identical, above current computation is equivalent to a voltage domain computation (voltage input to VI **264**)=(voltage input to VI converter **280**)–(voltage input to VI converter **260**), which performs the required subtraction computation between the motor voltage and current described previously. As a result, output from BEMF amplifier **274** which generates a BEMF voltage output that can be employed by a controller to control the motor **210**.

In order to determine BEMF, output from the resistance sense stage **230** can be combined with the voltage determinations in the motor BEMF stage **234** to compute the motor's BEMF. In this example, the current stage output is processed in the motor BEMF stage **234** via an additional VI converter **280** whose output is summed along with currents representing motor voltage and calibration at **270**. Thus, in this example, the motor BEMF **234** can be configured as a **6** input operational amplifier having a single output for BEMF in this example. An example of this configuration using multiple differential amplifiers driving a single operational amplifier is shown in FIG. **7**.

FIG. **3** illustrates an example of an integrated circuit **300** for a back electromotive force (BEMF) monitor that employs feedback to a motor calibration amplifier in a motor BEMF stage **334** to compute motor BEMF. In this example, a motor **310** is energized via motor power and common connections which can be supplied from a controller (not shown). Current from the motor **310** is sensed via current sensor **314** and voltage from the motor is sensed via voltage sensor **320**. The current sensor **314** and/or voltage sensor **320** can be provided by resistive networks, for example. The current sensor **314** generates a voltage proportional to the motor current where a motor current stage **330** determines a value for the motor's current. Output from the motor current stage **330** is fed to the motor BEMF stage **334**, which is configured to determine motor voltage via the voltage sensor **320**. Additionally, the motor BEMF stage **334** combines the current estimate from the motor current stage **330** with the motor voltage determination to compute a motor BEMF voltage, shown as BEMF, which can be sent to a controller to control the motor **310**.

A motor current input voltage-to-current (VI) converter **340** in the motor current stage **330** receives a motor current sensor voltage from the current sensor **314** and a reference voltage VREF to generate an output current related (e.g., proportional) to the motor's current. A motor current calibration VI converter **344** is configured to compensate for errors (e.g., gain errors, CMRR) in the motor current input VI converter **340** and generates a calibration output current based on the reference voltage VREF and the feedback from the output of BEMF amplifier **354**. The output current and the calibration output current of converters **340** and **344** are combined at a summing node **350** to form an estimate of the motor's current. Output from the summing node **350** is fed to a current stage amplifier **354** which generates an output that is fed back to the motor current calibration VI converter **344** and is also provided to the motor BEMF stage **334** for analog computation of motor BEMF.

A motor voltage input VI converter **360** in the motor BEMF stage **334** receives a motor sensor voltage from the voltage sensor **320** and the reference voltage VREF to generate an output current related to the motor's voltage. A motor voltage calibration VI converter **364** is configured to compensate for errors (e.g., gain errors, CMRR) in the motor voltage input VI converter **360** and generates a calibration output current based on the reference voltage VREF and the middle tap point of feedback resistor **380**. The feedback resistor **380** is tied to the output of current stage amplifier **354** on one end and tied to the output of BEMF amplifier **374** on the other end. The output current and the calibration output current from VI converters **360** and **364** are combined at summing node **370** to form an estimate of the motor's BEMF voltage. Output from the summing node **370** is fed to BEMF amplifier **374** which generates a BEMF voltage output that can be employed by a controller to control the motor **310**.

In order to determine BEMF, output from the motor current stage **330** can be combined with the voltage determinations in the motor BEMF stage **334** to compute the motor's BEMF. In this example, the current stage output is utilized by the motor voltage calibration VI converter **364** as feedback **380** (e.g., feedback resistor) which can be combined with the BEMF feedback from the BEMF amplifier **374**. Thus, a four input operational amplifier such as shown in FIG. **6** can be employed for the motor BEMF stage **334**. Similarly, the four input operational amplifier depicted in FIG. **6** can also be employed for the motor current stage.

FIG. **4** illustrates an example of a back electromotive force (BEMF) monitor circuitry **400** that employs an additional VI converter in a motor BEMF stage **450** to compute motor BEMF. In this example, a motor current stage **410** receives four inputs, including two inputs from a current sensor **440** and two related to reference VREF. The motor current stage **410** includes two VI converters **420** and **424** that are coupled to provide respective current outputs to a summing node **430**, which drives an amplifier **434**. The first VI converter **420** converts the voltage across a sense resistor **440** to a first output current I_{11}. The second VI converter **424** converts the difference between circuit reference e.g., VREF=0.9V and a tap-point of a feedback resistor path R411 into a second output current I_{12}. The first VI output current I_{11} and the second VI output current I_{12} are subtracted at summing node **430**, where the resulting difference is amplified by the amplifier **434** to provide a compensated indication of motor current. A feedback loop from amplifier **434** forces the input of the second VI converter **424** to be a copy of the first VI converter **420** input. Meanwhile, the voltage input of second VI converter **424**, which is a copy of the first VI converter **420**, is gained up by digitally programmable gain (e.g. 12-bit resistor DAC) set up by potential-meter R411. It is this gain that is digitally calibrated to be a ratio of motor resistor and sense resistor i.e. $G=R_M/R_{NS}$, which was described previously.

An aspect regarding why two VI converters are employed, is that the first VI converter **420** receives a high voltage common mode (e.g., 12V) signal from motor current sensor **440**. The switches processing the high voltage (HV) signal should be constructed to withstand high voltage for circuit safety considerations and they are considerably area consuming. Therefore, a minimum of two HV switches **444** are used to alter the circuit between normal operation mode (when VI **420** input is switched to sensor **440**) and offset calibration mode (when VI **420** input is switched to Vref). In contrast, the input of second VI converter **424**, which is a copy of voltage input of first VI converter **420**, can be in low-voltage (LV) domain (0.9+/−0.7V, i.e. from 0.2V to 1.6V), thus a large number of low voltage switches (not shown) can be employed for a 12 bit programmable gain DAC as illustrated as potentiometer R411, to avoid consuming large silicon area. In implementation, the two VI converters **420** and **424** are substantially identical in both schematic and layout, and they can be laid out next to each other in silicon such that the mismatching between the two converters is minimized.

In this example, a second stage **450** is configured to determine BEMF, and includes three VI converters **452**, **454**, and **456**. The VI converter **454** receives an attenuated version (e.g., divided by 6) of motor voltage via resistive divider network **458** and converts the detected voltage into a current shown as I21. The VI converter **452** receives output from stage **410** and converts it into I22. In one example, current from the VI converter **452** is multiplied by a gain factor (e.g., a factor of two) to provide I22. The VI converter **456** determines a voltage difference between circuit reference VREF and a feedback tap point of R412 to provide a compensation current I23. The output currents of three VI converters **452**, **454**, and **456** are combined at **460** to produce an error current (I_E) to an input of an output amplifier **464** (e.g., I_E=I21−I22−I23). The error current I_E is amplified by amplifier **464** and generates BEMF output, which can also fed back to VI converter **456** via digitally programmable potentiometer R412. The feed-back loop forces the input of the VI converter **456** to be a copy of difference of the input of VI converter **452** and the input of VI converter **454**, that is, $V_1-V_2=V_{VCM}/6-2\times V_{A1\_out}$ and meanwhile it is amplified by a programmable amplifier gain stage via potentiometer R412. An offset calibration DAC **470** (e.g., 6 bit DAC) can be used to cancel offset of whole BEMF stage **450** when both switches **480** and **484** are connected to VREF. Switch **480** can be periodically switched to provide samples of VREF (when stage **450** is configured in offset calibration mode) and the output from stage **410** to VI converter **452** (when stage **450** is configured as normal BEMF monitor mode). Switch **484** can be periodically switched to provide samples of VREF (when stage **450** is configured in offset calibration mode) and the output from network **458** to the VI converter **454** (when stage **450** is configured as normal BEMF monitor mode).

The resistors in the network **458** for signal attenuation do not have to be matched in high precision because any introduced gain error can be compensated by programmable gain for stage **410**. Also, since the substantially infinite input impedance of the stage **410** and the input stage **450** (e.g., VI converters), the low on-state resistance requirement on switches **444**, **480**, and **484** can be largely relieved. Therefore, the front node switch size can be reduced.

FIG. **5** illustrates a circuit example of a back electromotive force (BEMF) monitor **500** that employs feedback to a motor calibration amplifier in a motor BEMF stage to compute motor BEMF. A motor current stage includes a **4**-input amplifier **510**, a digitally programmable gain potentiometer R511 and an offset calibration DAC **514** (e.g., 10 bit DAC). The amplifier **510** includes two VI converters **520** and **524** which are coupled to form a summing node **530** which drives an amplifier **534**. The first VI converter **520** converts the voltage across a voice coil motor (VCM) sense resistor **540** to a current I_{11}. The second VI converter **524** converts the voltage difference between circuit reference (e.g., VREF=0.9V) and a tap-point of a feedback resistor R511 into a current I_{12}. The first VI output current (I_{11}) and the second VI output current

(I_{12}) are subtracted at summing node **530**, where the resulting difference is amplified by the amplifier **534**. Because of very high loop gain, the feedback loop (formed by amplifier **534** and potentiometer R511) forces the voltage input of the second VI converter **524** to be a copy of the first VI converter **520** input. Meanwhile, the input of VI **524**, which is a copy of the input of VI **520**, is amplified by programmable gain set by R511 to provide a corresponding amplified output. The amplified output from amplifier **520** is fed to VI converter **524** for gain cancellation. In implementation, the two VI converters **520** and **524** are nominally identical in both schematic and layout, and they can be laid out next to each other in silicon to mitigate mismatching between the two converters. As shown, a controllable switch **544** can switch between VREF (when stage **510** is configured as offset calibration mode) and the voltage across the sense resistor **540** (when stage **510** is configured as normal BEMF monitor mode).

In this example, the BEMF stage of FIG. **5** is implemented via two VI converters **554** and **566**. In the BEMF monitor, described above and shown in FIG. **4**, BEMF stage has three VI converters whose output current are connected as $I_{21}-I_{22}-I_{23}$. The subtraction operation between three elements implies that all of the three VI converters are required to have suitable linearity. However, in a dual VI converter BEMF stage **550**, the VI linearity requirement can be substantially relieved and the matching of the two VI converters takes precedence over VI linearity. As shown in FIG. **5**, instead of driving an additional VI converter to receive output from the stage **510**, output from stage **510** is fed to drive one side of gain resistor R512. A BEMF stage **550** includes a first VI converter **554** that receives a motor voltage via resistor network **558** and switch **560**. A second VI converter **566** receives a calibration input from offset calibration DAC **570** (e.g., 6 bit DAC) and output from current stage **510**. Output from VI converters **554** and **566** are combined at summing node **580**, which is then amplified via amplifier **584** to produce motor BEMF at its output. Output from amplifier **584** is fed back to the other side of R512 for stage gain control.

FIG. **6** illustrates an example of a four input operational amplifier **600** that can be employed in a BEMF monitor circuit. The amplifier **600** could be employed as the motor current stage **230** and **330** depicted if FIGS. **2** and **3** respectively. The amplifier **600** includes two VI converters **610** and **614**. The VI converters can be cross-coupled differential amplifiers and can be implemented as NMOS transistors and/or PMOS transistors. In this example, each VI converter **610** and **614** includes two pairs of PMOS devices that are cross coupled and stacked such that the VI conversion nonlinearity due to CMOS square law is cancelled out and VI transconductance is degenerated by R (shown as R61 through R64) The current output of these two VI converters **610** and **614** are subtracted before being loaded by R_L and fed into an operational amplifier **620**. The common mode rejection ratio (CMRR) of a VI converter can be written as:

$$CMRR = \frac{\Delta g_m R_L}{(g_{m1} + g_{m2})R_{SS}}$$

where g_{m1}, g_{m2} are respectively the trans-conductance of both input branches of the VI converter, Δg_m is the difference between the input pair trans-conductance due to any mismatching between two input branches, R_{SS} is the tail current impedance, and R_L is VI converter resistive load.

The CMRR can be largely attenuated by increasing the tail current impedance R_{SS}. To further achieve high CMRR, the tail current mirror impedance can be enhanced with very low cost gain boost stage such as shown at boost stage **630** and boost stage **640**. As shown, outputs from the VI converters **610** and **614** can be coupled to form a summing node at the input of the amplifier **620**.

FIG. **7** illustrates an example of a six input operational amplifier **700** that can be employed in a BEMF monitor circuit. The amplifier **700** could be employed as the BEMF stage **234** depicted in FIG. **2** and the BEMF stage **450** depicted in FIG. **4**. In this example, three VI converters **710**, **714**, and **718** can be configured to provide 6 inputs that drive an operational amplifier output stage **720**. Gain boost stages **730**, **740**, and **750** can be provided to increase the tail current impedance of each VI converter and thus enhance CMRR for each converter. Output from each VI converter can be coupled to form a summing node at the input to the amplifier **720**.

What have been described above are examples. It is, of course, not possible to describe every conceivable combination of components or methodologies, but one of ordinary skill in the art will recognize that many further combinations and permutations are possible. Accordingly, the disclosure is intended to embrace all such alterations, modifications, and variations that fall within the scope of this application, including the appended claims. As used herein, the term "includes" means includes but not limited to, the term "including" means including but not limited to. The term "based on" means based at least in part on. Additionally, where the disclosure or claims recite "a," "an," "a first," or "another" element, or the equivalent thereof, it should be interpreted to include one or more than one such element, neither requiring nor excluding two or more such elements.

What is claimed is:

1. An integrated circuit comprising:

a motor current input voltage-to-current (VI) converter that receives a motor current sensor voltage from a motor and a reference voltage that generates an output current related to a motor's current;

a motor current calibration VI converter that compensates for errors in the motor current input VI converter and generates a calibration output current based on the reference voltage, wherein the output current and the calibration output current are combined to form an estimate of the motor's current;

a summing node, which receives the outputs of the motor current VI converter and the motor current calibration VI converter and sums the output current and the calibration output current;

a stage amplifier that amplifies current from the summing node, wherein output from the stage amplifier is fed back to the motor current calibration VI converter and is fed to a back electromotive force (BEMF) stage, wherein the BEMF stage computes a BEMF voltage for the motor;

the BEMF stage further comprising:

a motor voltage input voltage-to-current (VI) converter that receives a motor voltage sensor voltage from the motor and a reference voltage that generates an output current related to the motor's voltage;

a motor voltage calibration VI converter that compensates for errors in the motor voltage input VI converter and generates a calibration output current based on the reference voltage, wherein the output current and the calibration output current are combined to determine an estimate of the motor's voltage; and an input VI converter that receives the output from the stage amplifier and generates a current relating to the motor's current to enable computation of the motor's BEMF voltage.

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